Investigation of the Reliability of Dams with Stochastic Finite Element Methods

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ABSTRACT: This investigation should illustrate the possibilities of stochastic finite element analyses of the dam safety using the example of an old gravity dam in Germany. The basis of the analysis is a parameterized and fully nonlinear 3D model of the dam and the foundation. Among other loads, transient temperature variations, pore water pressure and vertical anchors are taken into account. A sensitivity analysis with stochastic latin hypercube sampling is performed with the program *optiSLang*® using a total 200 designs (parameter combinations) with varying material parameters of the dam and the foundation. With displacement and pore water pressure measurement data and the parameter identification from the sensitivity analysis a fully calibrated finite element model is set up and the key for further investigation regarding failure probability analysis according to Eurocode. For the stochastic analysis of the dam, distribution functions for all relevant input parameters, e.g. flood events, are defined. Overall, again 300 nonlinear 3D finite element simulation are performed, whereby many different assessment criteria are investigated to find a suitable one for the global failure. After all, the evaluation of the stochastic analysis is done again with *optiSLang*®, which is capable to directly yield the failure probability P_f for a specific assessment criteria. Additionally, input parameters influencing the failure probability the most can be indicated quantitatively and qualitatively. Finally, it can be concluded, that the assessment of dams by stochastic analysis, in coherence with a calibrated nonlinear 3D finite element model, is feasible.

1 Introduction

Within the framework of an in-depth review of an old gravity dam in Germany [1], detailed safety assessments are carried out according to the latest state of standardization. The basis of these investigations is a three-dimensional finite element calculation model, which takes the effects and resistances into account as realistically as possible. The static calculations are carried out using nonlinear material laws for the dam (masonry) and brittle rock subsoil, considering the seasonal instationary temperature fields and the load-dependent pore water pressures in the dam body. Various scenarios regarding the effectiveness of existing sealing and drainage elements as well as the nature of the rock subsoil are to be considered.
The stability studies cover the following questions:

- Calibration and verification of the calculation model against measurement results,
- Stability assessment using the EC-compliant safety concept presented in [1] on the basis of partial safety factors,
- Basic studies on the behavior of the dam, taking into account spatial effects,
- Assessment of the reliability of the results and main impact factors,
- Stochastic investigations to assess the probability of failure

The calculations are carried out using the finite element program system ANSYS®, the elastoplastic material model library *multiPlas* [10] for ANSYS and the software for stochastic analysis ANSYS *optiSLang*® [9].

2 Nonlinear finite element model

For the continuum mechanical analysis, a 3D model of the dam and the foundation is created. The model size covers a width of 768 m, a length of 515 m and a height of 218 m. The FE model is shown in Figure 2.

The subsoil is modeled according to the data in [2], [3] and [5]. Accordingly, three zones of different permeability in the vertical direction have to be considered (see Figure 2). From [2] or [5] it is also clear that the foundation has different layers in the model area under consideration. On the right slope (up to the clay ridge located in the middle of the valley), clay slate is found with gray shackle benches in the investigations documented in [2]. On the left slope (up to the valley center), greywacke, with clay slate interlinings are found.

In order to simulate the nonlinear behavior of the masonry and the fissured rock subsoil, isotropic and anisotropic elastoplastic Mohr-Coulomb material models with tensile stress limitation are used. The position and orientation of the separating surface layers are also taken into account in the subsoil. In the masonry of the dam, a "virtual" horizontal separation surface is simulated to exclude vertical tensile stresses. Material parameters of the final calibration of the model can be found in Table 2. Figure 1 illustrates the constitutive models used for masonry dam, the intact rock and the joints.

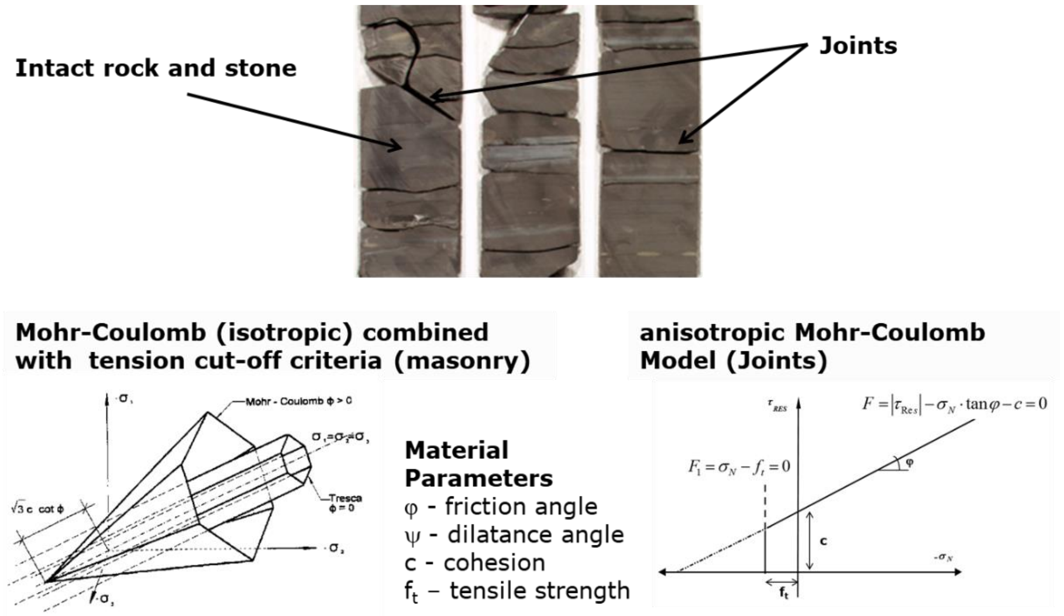

Figure 1: Constitutive models used for the masonry dam, the intact rock and the joints.

The grout curtain extends to a depth of +177.00 m a.s.l. in the region of the clay ridge and in the remaining region on both sides of the clay ridge to a depth of +191.00 m a.s.l.

A total of 104 anchors stabilize the dam in the middle area. Each anchor contains 34 strands. The cross-sectional area of each strand is 150 mm². The anchor force is 4500 kN/anchor. 52 anchors reach into a depth of +167.0 m and 52 into +172.0 m. The force introduction area (composite length) of the anchors in the rock is 10 m each.

Nonlinear static calculations are performed in all load case combinations. The mechanical boundary conditions are defined as roller bearings in the far field. Thus, the vertical deformations at the lower model edge and the deformations perpendicular to the lateral model edges are locked. The load history is taken into account in all load case combinations (LS) according to the composition in Table 1. The individual loads are multiplied by the corresponding partial safety factors [1].

For the determination of the temperature stresses of the dam (normal temperature event with or without impounded reservoir as well as extreme temperature event with impounded reservoir), non-stationary thermal finite element calculations are carried out. The data from [7] is used as a basis for the year of external temperatures in the Hessen region. The water temperatures are taken into account in the thermal calculations as a function of time and water depth according to temperature data available at BAW (Federal Waterways Engineering and Research Institute). The 3D pore water pressure fields are calculated using ANSYS by means of transient thermal analysis using a temperature-flow analogy. The hydraulic analysis is based on the model for seepage flows in the fractured rock according to Wittke [8]. The calculation is performed iteratively to determine the free surface area in the dam.

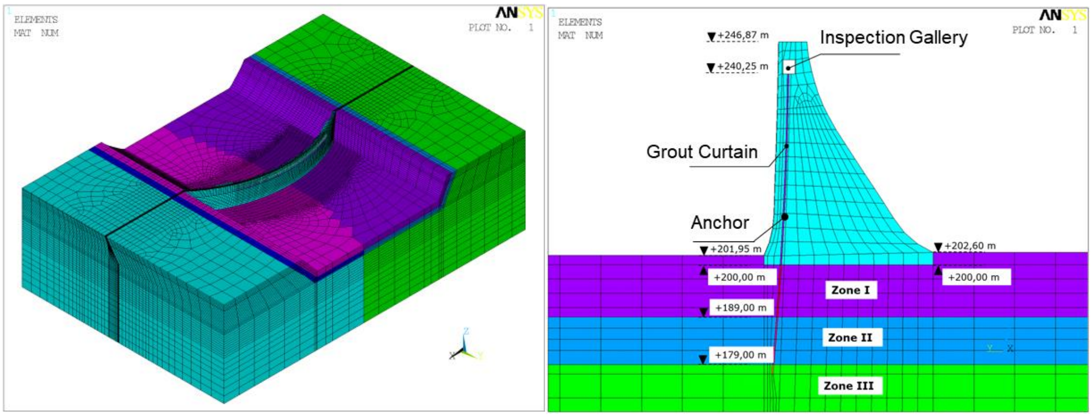

Figure 2: 3D FE-model of the dam and the dam section.

Table 1: Load steps of the nonlinear simulation.

Loadstep	**Action**
LS1	Deadweight Foundation (Initial Stress State)
LS2	Deadweight Dam
LS3	Hydrostatic Water Pressure for defined Water Level
LS4	Hydrostatic Water Pressure at the Level of anchor pre-stressing (241,605 m NN)
LS5	Anchor activation
LS6	Anchor Pre-Stressing
LS7	Hydrostatic Water Pressure for defined Water Level
LS8 f.	Additional varying loads according to Eurocode [1]

3 Model calibration and verification

In order to increase the realistic proximity of the simulation model and thus to achieve a high quality of the stability tests, the simulation model is compared by parameter identification with available measured values of the dam. For this calibration, deformation measurements (plumb measurements and triangulation measurements) are available. The triangulation values are less accurate because of the temperature influences. They are therefore included in the model calibration only with a lower weight (50%). The position of the deformation points measured is shown in Figure 3. Furthermore, pore water pressure and temperature measurements could be used to verify the hydraulic and thermal analyses.

In the first step of the parameter identification, a sensitivity analysis is carried out to determine the dependencies between the model parameters and the response variables to be calibrated, and the scattering range of the numerical model compared to the measured values.

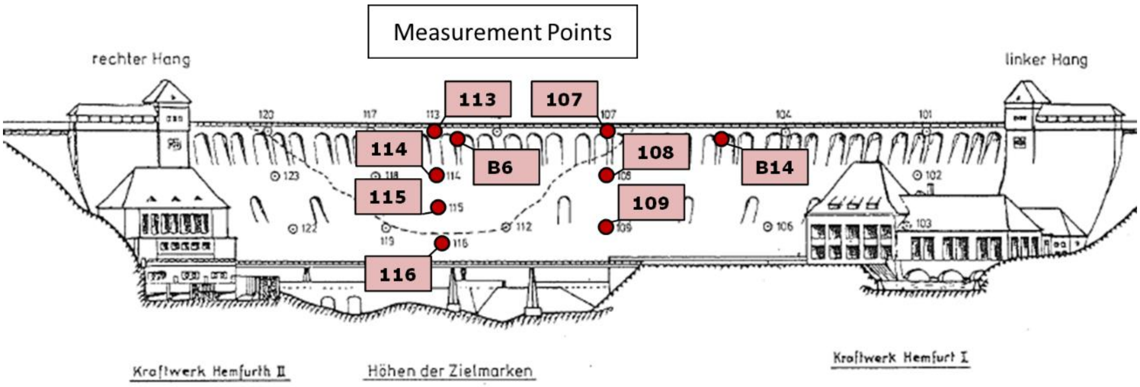

Figure 3: Displacement measurement points

The sensitivity analysis is carried out by means of variations-based correlation analysis in ANSYS optiSLang® [9]. The material parameters of the wall and the subsoil between minimum and maximum limits are varied as scattering input parameters of the sensitivity analysis. The radial relative displacements at the measurement points indicated in Figure 3 are used as response variables. Within the framework of the sensitivity analysis, 200 parameter combinations (designs) are calculated. The stochastic Latin Hypercube sampling available in ANSYS optiSLang® [9] is used for sampling the 200 designs. In each design, a nonlinear load history calculation is simulated with the following load steps for calibration (LSC):

- LSC1 Activation of the dead weight in the foundation (Initial stress state)
- LSC2 Activation of the dead weight of the dam
- LSC3 Hydrostatic Water Pressure at 229,02 masl
- LSC4 Hydrostatic water pressure at minimum water level (220,00 masl)
- LSC5 Hydrostatic water pressure at maximum water level (244,95 masl)

Since the measured values of the deformation measurements originate from the time before the rehabilitation and the installation of the pre-stressed anchors, the dam is simulated in sensitivity analysis and model calibration without anchors and restoration measures.

The results of the sensitivity analysis are shown as an example for measuring point B6 (see Figure 3). The relevant input parameters (CoP values as a bar histogram) for the maximum water level (244.95 masl) and the minimum water level (220.00 masl) are calculated for each measuring point and the associated dependencies (anthill plots of the relevant input parameters vs. deformation). The CoP values are prognosis parameters and indicate how much the variance of the observed response variable (deformation at the measuring point) can be explained by the variation (or variation) of the respective input variable. Unimportant input parameters (whose scatterings are not correlated with the spread of the response variable) are automatically filtered out by ANSYS optiSLang® [9]. As the sensitivity analysis shows, the stiffnesses of the subsoil and of the masonry of the dam can be calibrated in particular by means of the deformation measurement values for the observed / measured water levels. The foundation stiffness of the left and right slopes can be combined (symmetry of the dependencies and deformation measurements, see, for example, MP4 / MP14, MP 109 / MP 115). It is also plausible that the stiffness of the masonry has a greater influence on the higher measuring points, whereas the deformation on the MP 116 is almost exclusively determined by the foundation stiffness. Figure 5 shows the calculated and measured deformations. The black line indicates the measured values, gray lines indicate the spread of all designs and red is the best design Nr.186, which is determined by optimization and shows a very good agreement with the measured deformation values. As a result of the model calibration, a simulation model is developed which can easily and reasonably reconstruct the available measurements with regard to the deformations, temperatures and pore water pressures.

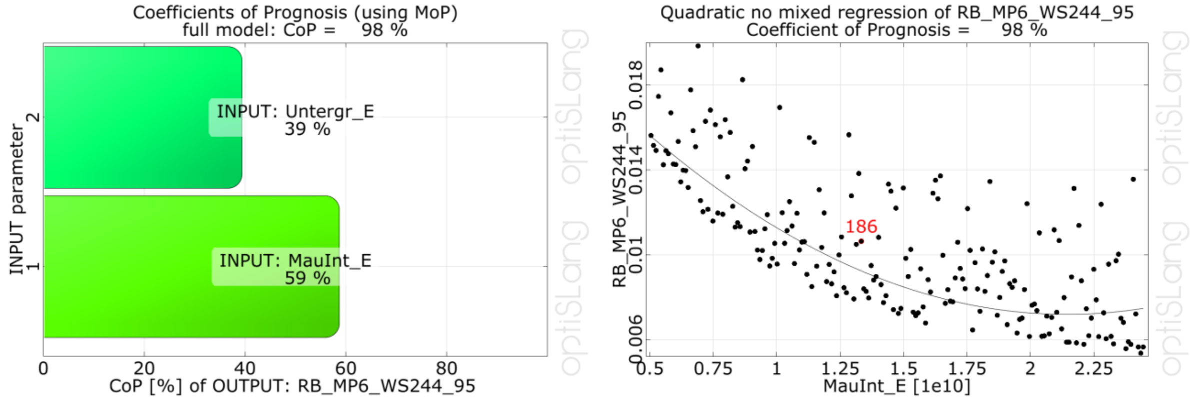

Figure 4: Results of the sensitivity analysis for measurement point B6;
left: Histogram of CoP; right: Anthill-Plot of the E-modulus of the dam (MauInt_E) vs. radial displacement at measurement point B6

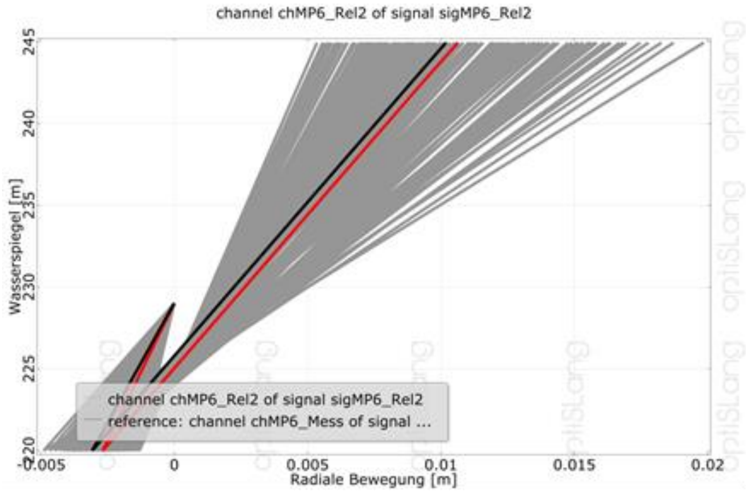

Figure 5: Radial displacement of measurement point B6, Grey: Band width of all designs;
Red: Best design Nr. 186; Black: Measurement.

Table 2 summarizes the calibrated material and joint parameters for the dam and the foundation. Zones are depicted in Figure 2.

Table 2: Calibrated Material Properties.

	Dimension	**Masonry**	**Intact Rock**		
Density	t/m³	2.2	2.72		
E-Modul	N/mm²	11100	4697		
Poisson ratio	-	0.25	0.257		
Compressive strength	N/mm²	5	20		
Friction angle	°	45	45		
Cohesion	N/mm²	1.0355	4.14		
Tensile strength	N/mm²	0.5	2		
Residual friction angle	°	31.5	31.5		
Residual cohesion	N/mm²	0.1036	0.4142		
Residual tensile strength	N/mm²	0	0		
Reference temperature	°C	10	8		
Thermal expansion coefficient	K^{-1}	1E-5	1E-5		

		Horizontal Joint	1. Joint Zone 1	2. Joint Zone 2	3. Joint Zone 3
Alpha	°	90	70	160	115
Beta	°	0	90	90	90
Friction angle	°	45	30	30	30
Dilation angle	°	20	10	10	10
Cohesion	N/mm²	0.5	0.1	0.1	0.1
Tensile strength	N/mm²	0	0	0	0
Residual friction angle	°	21.8	21	21	21
Residual cohesion	N/mm²	0.25	0.05	0.05	0.05
Residual tensile strength	N/mm²		0	0	0

4 Structural analysis

On the basis of the Eurocode safety concept presented in [1], a safety assessment is carried out. A total of 8 load cases are calculated using the calibrated nonlinear 3D simulation model. Using the shear stress criteria according to Mohr-Coulomb with tensile stress limitation, the shear stress proof in all spatial directions and the tensile stresses in the (virtual) horizontal joints of the dam and all spatial directions are limited. The relative displacements (see Figure 6), the load displacement history, principal, horizontal and vertical stresses (see Figure 7), plastic strains / zones of gaping joints and plastic activities as well as the achievement of a converged equilibrium solution are used for the assessment.

Opening of horizontal joints are identified by means of plasticity from the simulations. A crack opening and thus a gaping (water-bearing) joint can only occur when the fracture energy dissipates under tensile and shear stress and the cracking elongation of the fracture brickwork is reached or exceeded. When a crack width of $w_{crit} \geq 0.15$ mm is assumed as the water-bearing crack width, a critical plastic strain value of 0.5 ‰ results for an average stone size of approx. 30 cm. This means that a completely unhindered hydraulic permeability (cracking water pressure) is considered instead of the permeability applied in the initial model for cross-sectional areas in the wall in which the plastic strains exceed 0.5 ‰.

Solutions are found for all stressed load cases and the assessment criteria are adhered to the Eurocode safety concept [1]. This means that, under consideration of the assumptions and idealizations made, the stability of the dam for the required safety values is established.

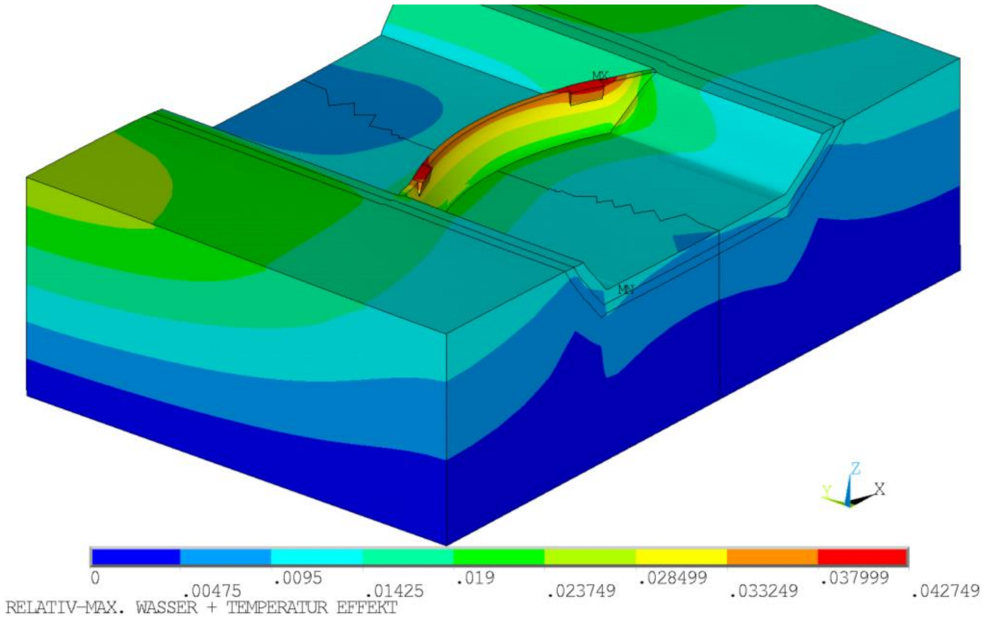

Figure 6: Load case 1 – SBS1: Displacement uSUM (m), all loads

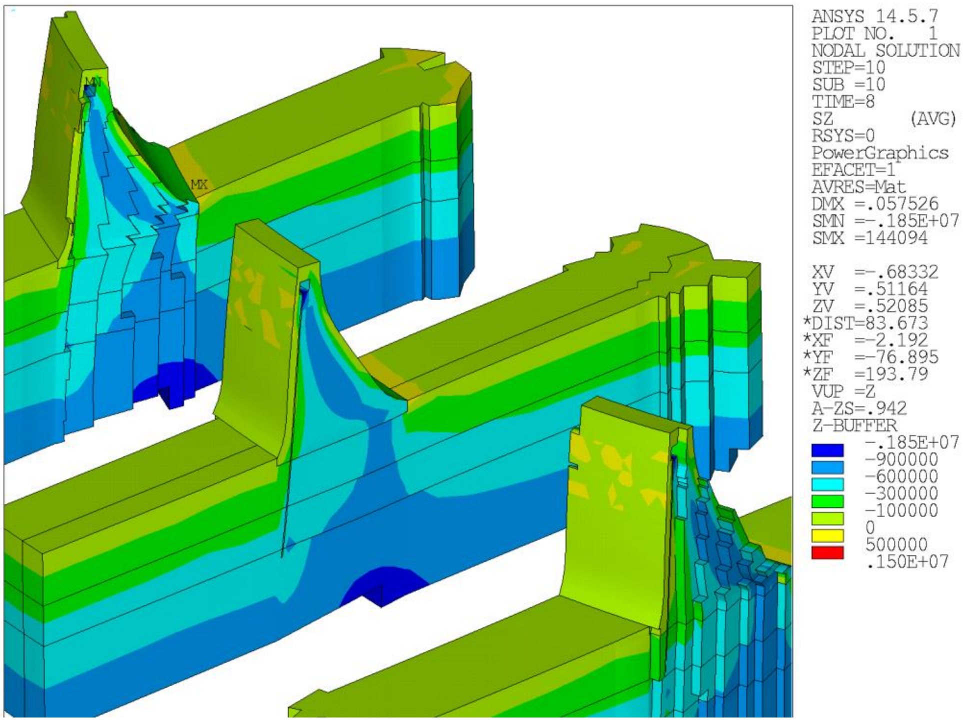

Figure 7: Load case 1 – SBS1: Vertical stresses σ_z (Pa), all loads

5 Stochastic analysis

Based on the stability studies, a stochastic analysis is carried out using the calibrated FE model to evaluate the failure probability of the dam.
The motivation for the stochastic analysis results from several questions. For example, a stochastic analysis can be used to circumvent contradictions arising from the use of partial safety factors in nonlinear analyzes. Another issue is the question of the safety level of an existing building. It is, of course, possible, in principle, to provide a proof of stability by means of a concept based on safety factors (see section 4). However, if an existing safety level is to be predicted on this basis until the building fails, the question arises as to whether it should be determined by a load-side increase or by a reduction of the resistance. Both approaches aren't without doubt possible in connection with nonlinear analyzes.
By means of a stochastic analysis, failure probabilities can also be determined in the case of nonlinear analyses when introducing load and resistance-side scatterings. This procedure is included in EN 1990:2002 (Annex B and C). In a recent cooperation between the BAW (Federal Waterways Engineering and Research Institute) and Dynardo, the example of this dam is worked out, including further fundamental investigations, to develop a procedure for practical projects.
The stochastic analysis consists of the following steps:

- Definition of the scattering of the input parameters:
  For this purpose, distribution functions are assumed in coordination for all relevant input parameters of the calculation model (material characteristics and loads) based on the mean value, the characteristic value and known probabilities of extreme events (such as BHQ10000). (see Table 3)
- Generating the samples:
  300 samples are generated. In ANSYS optiSLang® [9], various methods (Monte Carlo, Latin Hypercube, Directional Sampling, FORM, ...) are available for this purpose. As a first analysis, Latin Hypercube sampling with 300 samples is used for the calculation of

the probability of failure. This can be understood as an extrapolation based on the distribution of the failure criteria. Figure 8 shows the distribution function of the failure condition under consideration in comparison to the probability of failure according to Eurocode. However, additional investigations with FORM or other methods are in discussion and part of the ongoing cooperation with BAW (Federal Waterways Engineering and Research Institute).

- Definition of evaluation criteria:
  The evaluation parameters for the stability (tilt safety - position of the resultant, sliding safety - principal shear strain, pressure failure - principal normal strain and risk of fracture in the grouting zone - max. plastic vertical strain) are defined as the basis for the detection concept presented in [1].
- Performing nonlinear analyses:
  300 nonlinear analyses are performed using a compute cluster at Dynardo with up to 256 CPUs within 4 days. Therefore, the most relevant load case combination from section 4 is used.
- Evaluation and determination of the probability of failure
  The evaluation is carried out in representative sections of the dam. In ANSYS optiSLang® [9], various results and output options are available for the evaluation of a stochastic analysis. In Figure 8, the distribution and probability of failure calculated from the stochastic analysis are illustrated by the example of the eccentricity of the force-resultant at the base. Therefore, the eccentricity of e>d/3 is the defined fictional limit state. The calculated probability of failure P_f is 1.92E-06 (Figure 8), which is below the required value of P_f = 1.0E-05. The reliability index β is 4.62 and is greater than the required value of 4.27.

  In addition to the calculation of the probability of failure, the influencing parameters which are decisive for the distribution of the response variable can be output both qualitatively and quantitatively in ANSYS optiSLang® [9]. This allows statements to be made as to which stray input variables (loads, resistances) are relevant for the failure of the dam.

Table 3: Examples of input scattering of parameters (17 out of 72 parameters).

Masonry Dam Parameter	**Dimension**	**Mean value**	**Standard deviation**	**COV [%]**	**Distribution function**
Density	t/m³	2.2	0.176	8	Normal
E-Modul	N/mm²	11100	1950	17.6	Log-Normal
Poisson ratio	-	0.25	0.05	20	Log-Normal
Friction angle	°	45	-	-	Constant
Cohesion	N/mm²	1.0355	0.69	40	Log-Normal
Tensile Strength	N/mm²	=0.1*Cohesion*(2*cos(45°)/(1-sin(45°)))			Dependent
Intact rock Parameter	**Dimension**	**Mean value**	**Standard deviation**	**COV [%]**	**Distribution function**
Density	t/m³	2.72	-	-	Constant
E-Modul	N/mm²	4697	1250	26.6	Log-Normal
Poisson ratio	-	0.257	0.057	22.2	Log-Normal
Friction angle	°	45	-	-	Constant
Cohesion	N/mm²	4.14	2.76	40	Log-Normal
Tensile Strength	N/mm²	=0.1*Cohesion*(2*cos(45°)/(1-sin(45°)))	-	-	Dependent

1. Joint – Zone 1	Dimension	Mean value	Standard deviation	COV [%]	Distribution function
Alpha	°	110	2.5	2.3	Normal
Beta	°	90			Constant
Friction angle	°	30	6	20	Log-Normal
Dilation	°	12.5	-	-	Constant
Cohesion	N/mm²	0.1667	0.067	40	Log-Normal

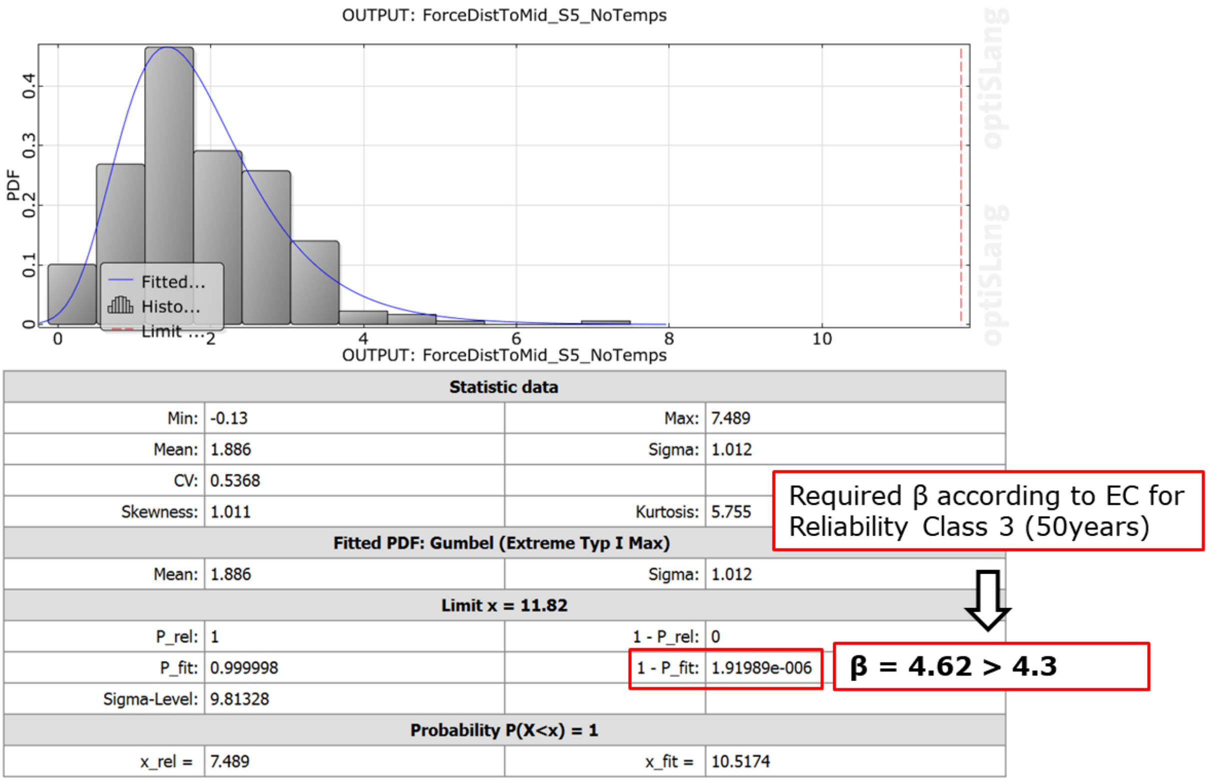

Figure 8: Calculated distribution and failure probability of the assessment criteria (here: eccentricity of the resultant force at the dam-foundation contact)

6 Conclusion and outlook

Static finite element calculations (3D) are carried out using nonlinear material laws for the dam and the foundation, taking into account the seasonal instationary temperature fields and the load-dependent pore water pressures in the dam body. The FE calculation model used is calibrated on available measurement results. The proof of stability is successfully implemented using partial safety factors according to an EC-compliant safety concept developed by the customer. In addition to this, the probability of failure of the dam is determined by a stochastic analysis against various evaluation criteria. It is shown that the definition of the assessment criteria influences the magnitude of the failure probability. Further systematic investigations are to be carried out in a co-operation between the BAW (Federal Waterways Engineering and Research Institute) and Dynardo in order to elaborate basic statements on the definition of these assessment criteria for the stochastic analysis.

7 Acknowledgements

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8 References

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